

Maximising Natural Gas Recovery from Class-1 Hydrates

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ABSTRACT

Natural gas, a non renewable source of energy can be found trapped inside the earth's surface in form of gas hydrates. Recovery of gas from class 1 gas hydrate reservoirs using depressurisation techniques can be simulated using the reservoir-tank model. This paper extends the analysis of the Oregon site using this model. It studies the effect of deliverability constant on the gas recovery. The paper also argues that shutting down of the well at non equilibrium pressures actually leads to pressure build up in the well due to hydrate dissociation which in turn increases net recovery of gas from the well. We analyse sequential closing and opening of the well at different dissociation rates for the hydrate as a method to maximise the net recovery of gas from the well in a fixed time span.

Keywords: Natural gas, Recovery increase, Hydrates, Shut down

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1. INTRODUCTION

Non renewable sources of energy have been in continual demand for over three centuries now. Natural gas or Methane is a widely used non renewable source of energy. Natural gas and oil are generally found together below the earth's surface where the gas is trapped between the cracks of rocks. Another form in which natural gas occurs is in the form of hydrates. A natural gas hydrate is a methane molecule trapped inside water molecule cage. The abundance of such reserves is almost four times more than the known coal reserve. Large abundance of hydrate reserves and higher calorific value of methane are going to play an instrumental role in making natural gas hydrates next big thing in Energy industry. The hydrates are generally classified into four classes on the basis of how they occur inside the surface. Class 1 hydrates are those hydrates where a layer of hydrates exists above a free natural gas layer. In the present study we have tried to study recovery of gas from a class 1 hydrate and how to increase the recovery from such a hydrate.

2. MODEL

The model was applied to a site in Oregon which was in the category of class 1 hydrates. A potentially significant source of methane hydrate lies eighty kilometres off the coast of Oregon, USA (Trehu and Fleuh, 2001). The site is evaluated using the tank reservoir model (Khatanair, 2002). The value for different parameters useful in the modelling and their values for the site are mentioned in the Table 1. A homogeneous and isotropic hydrate layer is assumed to be on a free gas layer. The reservoir is assumed similar to a tank where the gas obtained from well is comprised of initial free gas as well as gas obtained from dissociation. The dissociation is considered analogous to ice melting-it occurs along the front inside of the entire volume (Ahmadi 2004). The tank reservoir model assumes that the reservoir behaves as a tank and there is only one centrally located production well. This reservoir is assumed to be homogenous and isotropic with a hydrate zone and a free gas zone beneath. The driving force for dissociation is only depressurisation. In the hydrate zone there are three phases assumed - hydrate (solid), natural gas (gas) and water (liquid). Instantaneous equilibrium in terms of pressure and temperature is assumed throughout the gas zone. The reservoir behaves as a closed system with no mass or energy transfer through its boundaries. Lastly it is assumed that there is no free water in the reservoir and all the water present is produced due to hydrate dissociation. In a typical class 1 hydrate there is a layer of hydrate over a layer of free gas. In the tank model, let the hydrate layer be of height h_{Hg} there is only single hydrate phase present in this layer and it is assumed that all the water and free gas produced goes to the lower layer. At any instant the height of hydrate layer is h_H changed from the initial hydrate layer length of h_{Hi} . In a typical class 1 hydrate there is a layer of hydrate over a layer of free gas. In the tank model, let the hydrate layer be of height h_{Hg} there is only single hydrate phase present in this layer and it is assumed that all the water and free gas produced goes to the lower layer. At any instant the height of hydrate layer is h_{Hg} changed from the initial hydrate layer length of h_{Hi} . The hydrate decomposes at the equilibrium pressure of P_{eq} , which at the isothermal conditions of 6°C is 5400 KPa and the water and gas influx from this dissociation is W_{eH} and G_{eH} . The molar rate of dissociation of hydrate is (Kim et al, 1987).

$$\frac{dG_{zH}}{dt} = K_s A_s \left(\frac{P}{P_{eq}} \right) (P_{zH} - P)$$

Table 1
Nomenclature

Symbol	Meaning	Value(if any)
A	Reservoir area (m ²)	1500
B _g	Gas formation volume factor	-
B _{gi}	Initial gas formation volume factor	-
B _{gH}	Hydrate formation volume factor	-
B _w	Water formation volume factor	-
G _p	Gas produced (m ³)	-
G _{eH}	Gas influx from hydrates(m ³)	-
G _{fi}	Initial free gas in place(m ³)	-
G _{fr}	Remaining free gas (m ³)	-
G _{Hi}	Initial hydrated gas in place (m ³)	-
G _{Hr}	Hydrated gas remaining(m ³)	-
h _H	Hydrate zone thickness(m)	-
h _{Hi}	Initial hydrate thickness (m)	115
h _{gi}	Initial gas zone thickness (m)	300
P _i	Initial reservoir pressure,(KPa)	5400
P _{wf}	Flowing wellbore pressure, (KPa)	1600
q _g	Gas production rate, (m ³ /s)	-
q _w	Water production rate, (m ³ /s)	-
S _w	Water saturation in the gas zone at time t	-
S _{wi}	Initial water saturation	0.15
W _p	Water produced, (m ³)	-
W _{eH}	Water influx from hydrates, (m ³)	-
φ	Porosity	0.2

Where, $K_g = 2.2838 \times 10^{17}$ scf gas/acre-psi-day

And $\frac{r}{\alpha} = 16950^\circ R = 9416.666K$

Also, The water influx is given by $W_{eH}=0.00083 \times G_{eH}$

The free gas layer contains free gas and water and the saturation is S_{wi} initially. As the hydrate decomposes, this layer increases to h_g and saturation becomes S_w . The gas at any point in the system from dissociation of hydrate is G_{eH} . The pressure at any point in this layer is P. The gas and water is continuously removed from the layer through a well. The well flowing pressure is P_{wf} and is 1600 KPa. The water produced from the well is W_p and the gas produced is G_p .

The rate at which gas is obtained from the well is modelled as

$$Q_g = \frac{dG_g}{dt} = C \times \sqrt{P^2 - P_{wf}^2} \quad (C \text{ is in m}^3/\text{s/KPa})$$

The pressure P of the free gas is slowly decreased to this pressure P_{wf} .

The rate at which water is obtained from the well is

$$Q_w = \frac{dW_p}{dt} = \frac{\mu_g K_w h_g}{\mu_w K_g h_w} Q_g$$

The whole tank is assumed to have a surface area of A and porosity of the equations is reached by the understanding that in the whole process the volume of the system is conserved. The changes in volume of the three phases are considered separately and the net change in volume is equated to 0.

$$\begin{aligned} \text{Change in the volume of Hydrate} &= \Delta V_H = (G_{Hi} - G_{Hf})B_H \\ &= A\phi(1 - S_{wi})\Delta h_H \end{aligned}$$

$$\begin{aligned} \text{Change in the volume of Water} &= \Delta V_W = (W_p - W_{eH})B_w \\ &= A\phi[S_{wi} \times h_g - S_w \times (h_g + \Delta h_g)] = A\phi(S_{wi} - S_w)h_g \end{aligned}$$

Change in the volume of Gas = Volume change due to pressure conditions change + Volume change due to gas production

$$\text{Volume change due to pressure conditions change} = G_{fi}(B_{gi} - B_g)$$

$$\text{Volume change due to gas production} = (G_p - G_{eH})B_g$$

$$\text{Total Change in volume of Gas } \Delta V_g = G_{fi}(B_{gi} - B_g) + (G_p - G_{eH})B_g$$

$$\text{Total volume change of Reservoir} = 0$$

$$\Delta V_H + \Delta V_W + \Delta V_g = 0$$

$$\Rightarrow (G_{Hi} - G_{Hf})B_H + (W_p - W_{eH})B_w + G_{fi}(B_{gi} - B_g) + (G_p - G_{eH})B_g = 0$$

3. METHODOLOGY

The volume changes of hydrate, free gas and water amount give the total change in volume of the system. In the reservoir model this change of volume is assumed to be zero and thus one equation is obtained. Differentiating this equation with respect to time gives an equation explaining the variation of Pressure. Further, the volume formation factors were calculated using gas laws and the kinetics equation which was taken from Kim et al (1987). The system thus could be modelled using three coupled differential equations in P, h_g and S_{wi} . These equations were then solved in MATLAB. The initial conditions for solving are taken as follows

Table 2

Pressure at the end of every 100 seconds in an open well
($C=0.05 \text{ m}^3/\text{s/KPa}$)

Time(s)	Pressure(KPa)
0	5400
100	4394
200	4474
300	4020
400	3563
500	3146
600	2735
700	2356
800	2024
900	1767
1000	1621

Table 3

Optimal set C_i for which recoverable gas is maximised (C_i in $\text{m}^3/\text{s/KPa}$)

i	C_i	Time Elapsed(s)
1	0.1	100
2	0.1	200
3	0.1	300
4	0.1	400
5	0	10400
6	0.1	10500
7	0.1	10600
8	0	20600
9	0.1	20700
10	0.1	20800

$P=5400 \text{ KPa}$, $h_g=300 \text{ m}$, $S_{wi}=0.15$.

Results of the simulation are discussed in the next section.

4. SHUT DOWN

The results of the section above show that the pressure in the well falls very rapidly with the time for which the well is opened. The reservoir pressure at the end of first 100 seconds of opening the well is found to be 4934KPa. The fall in the pressure at the end of every 100 seconds when compared to initial pressure is reported in the Table 2. If a well at a pressure less than the equilibrium pressure is currently not used to obtain gas, it is said to be in shut down. This shutting down of the well can actually increase the net recoverable gas from the well by promoting decomposition of the gas hydrate above the free gas layer. Pressure difference from equilibrium pressure is the driving force of this dissociation. The decomposition of the hydrate continues until the equilibrium pressure is re-established in the well, which is 5400Kpa for given conditions. The equations for pressure and volume variation during a shut down were solved in MATLAB with initial conditions being the conditions at the end of first 100 seconds for an open well. The variation of pressure with the time passed was studied and plotted. It takes around 12000 days for the pressure to come very close to the equilibrium pressure, without ever actually becoming equal. It is practically impossible to shut the well down for 12000 days and then reopen it again thus continuing the cycle. However, the gain in total recovery due to shut down for a short time is also considerable and can be utilised when maximising the overall recovery in a given time span.

5. INCREASING RECOVERY BY SEQUENTIAL OPENING AND CLOSING OF THE WELL

The results in the previous sections show that pressure is build up in the well if it is shut down after opening it for some time. The initial equilibrium pressure is retained. For a typical well, the pressure at the end of first 100 seconds is 4934KPa. If the well is shut down thereafter; the time to regain the equilibrium pressure is around 12000 days. The shutting down though doesn't contribute to gas flow but builds the pressure which increases the recovery if the well is subsequently opened. Though this sequential opening and closing of the well is practically infeasible, we should not under appreciate the increase in the gas recovery due to a shut-down. The effect of shut down and corresponding pressure build was studied when the gas obtained from the well for a given time is optimised. Let's say we have to make 10 choices of C for a given well. If C is non zero that means well is opened for 100 seconds with C equal to the chosen value. On the other hand we can choose C to be zero and assume the well is shut down for 10000 seconds and the rate of dissociation is 10^5 times more than normal rate. The rate can be increased by either decreasing the energy barrier (E) by catalysis or increasing the temperature (T) of the well or both. So we can either choose to operate the well for 100 seconds at a non-zero value of C or shut it down for a 10000 seconds and a increased dissociation rate by a factor of 10^5 .

C ($\text{m}^3/\text{s/KPa}$)	Time(seconds)	Status
(0,0.1]	100	Open
0	10000	Shut down

In other words, we need to choose C_i for $i=1$ to 10. The selection should be such that the total gas recovery from the well is maximised. The code is implemented in MATLAB where a random initial guess of C_i for $i=1$ to 10 is generated using `randi()`. This guess is then improved such that the obtained gas from the well increases with every improvement in the guess. Finally an optimum set of C_i for $i=1$ to 10 is returned by the obtained gas maximizer function. To obtain a more reliable optimum set of C_i the process is repeated a large number of times. The optimum set of C_i that is obtained maximum number of times is reported as the final optimum set (Table 3).

6. RESULTS

- The Graph 1 shows the fall in the reservoir pressure with the time for which the well has been left open. The initial pressure is equilibrium pressure at 6°C which is 5400 KPa. It can be seen that only within 1000 seconds which is only 16.67 minutes, the reservoir pressure reaches the well pressure of 1600 KPa.
- The well deliverability constant(C) also has an effect on the drop in the pressure of the reservoir. The Graph 2 shows that for larger values of C the pressure falls more rapidly, as is expected.
- The pressure in a closed well as a function of the time (in days) is shown in Graph 3. The equilibrium is re-established after only around 12000 days which is a very long time when compared to 100 seconds for the pressure to fall to this value.
- The initial guess for $C_i=0.01$ `randi(0,10)`. The guess is improved continuously by the `fval` function in MATLAB so that the obtained gas is maximised.
- The C_i values for which the total gas is maximised are given in Graph 4.

7. CONCLUSION

The analysis explains a lot about the nature of the class 1 hydrates and also help to look into future ways to increase the gas recovery from a given site. The study shows that it is almost practically infeasible to obtain significant continuous flow of gas from a class 1 hydrate at the given site. The shutting down of well increases the pressure build up inside the well. Therefore, the total recovery from the well can be increased by sequential opening and closing of the well where during the shut-down hydrate dissociates and increases the total free gas in the well. The dissociation rate during shut down should be increased appropriately to make the recovery significant thus making the process economically feasible.

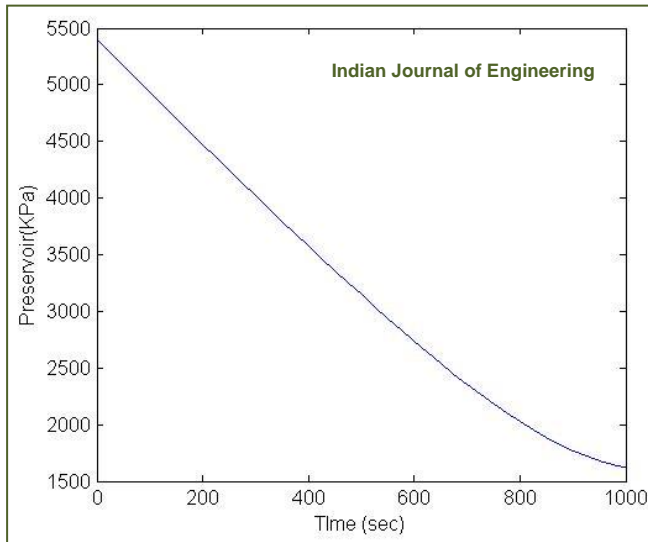


Figure 1
Reservoir pressure versus the time

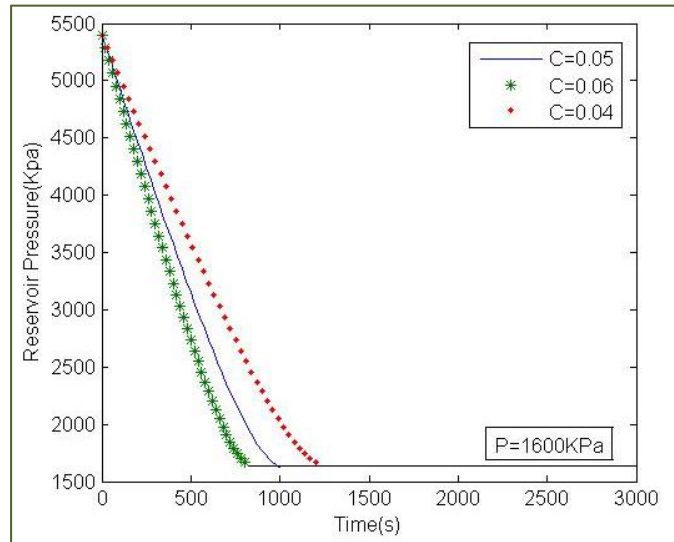


Figure 2
Effect of C (in $\text{m}^3/\text{s/KPa}$) on the pressure in the reservoir

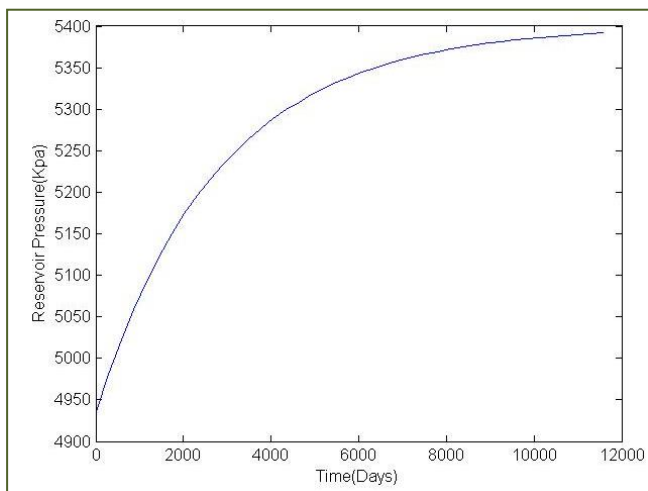


Figure 3
Pressure built up in a closed well

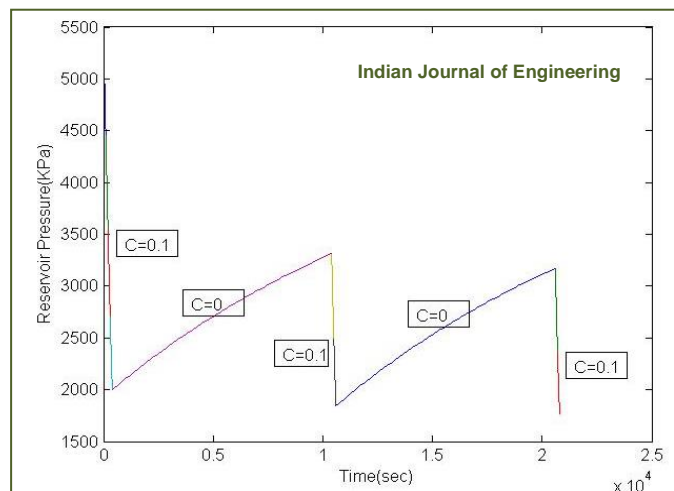


Figure 4
Sequential closing and opening of well to optimise gas recovery. (C_i in $\text{m}^3/\text{s/KPa}$)

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